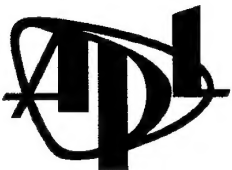


Bubble Attenuation Effects in High-Frequency Surface Forward Scattering Measurements from *FLIP*

by Peter H. Dahl

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Applied Physics Laboratory University of Washington
1013 NE 40th Street Seattle, Washington 98105-6698

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ABSTRACT

Measurements of surface forward scattering loss between 20 and 50 kHz were made from the research platform *FLIP* in January 1992. These measurements were analyzed for residual loss (defined as the loss in excess of spreading and chemical absorption), which is attributed to bubbles and referred to as surface bubble loss (SBL). With these data, a new, semiempirical model for SBL was developed that improves upon a model currently used. SBL is a key input parameter for predicting bubble attenuation in simulations of weapon system performance in near-surface environments.

EXECUTIVE SUMMARY

The Applied Physics Laboratory at the University of Washington (APL-UW) conducted measurements of forward scattering loss between 20 and 50 kHz from the research platform *FLIP* off the coast of California in January 1992. This work was sponsored by the Office of Naval Technology with technical management by the Applied Research Laboratory, Pennsylvania State University. The main objective was to obtain coordinated measurements of acoustic surface scattering, the subsurface bubble field, and the sea state in order to

- understand more fully the conditions imposed by the near-surface environment that affect the performance of sonar signal-processing algorithms
- improve high-frequency acoustic models used in sonar system simulation, modeling, and analysis.

The surface forward scattering loss measurements were analyzed for residual loss (defined as loss in excess of spreading and chemical absorption), which is attributed to bubbles and referred to as surface bubble loss (SBL). A new, semiempirical model for SBL is developed from the data that improves upon a current model for SBL. The new model predicts the mean energy loss in surface bounce paths that is due to extinction from near-surface bubbles. SBL is a key input parameter for predicting bubble attenuation for simulation and analysis of sonar system performance in near-surface environments.

The new model is

$$\begin{aligned} \text{SBL (dB)} &= \frac{1.26 \times 10^{-3}}{\sin \theta} U^{1.57} F^{0.85}, & U \geq 4 \text{ m/s} \\ \text{SBL (dB)} &= \text{SBL}|_{U=4} e^{10(U-4)}, & U < 4 \text{ m/s}, \end{aligned}$$

where U is wind speed measured 10 m above the sea surface, F is acoustic frequency in kilohertz, and θ is the nominal grazing angle of the surface bounce path ($\theta \geq 0^\circ$). The model includes a wind speed threshold of 4 m/s to account for the threshold of breaking waves (Beaufort velocity) and subsequent production of bubbles.

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1. INTRODUCTION

This report presents results of surface forward scattering loss measurements made in the open ocean between 20 and 50 kHz. It also describes a new model for predicting surface loss due to bubbles, based on these measurements.

The measurements were made from the research platform *FLIP* off the coast of California in January 1992. The objective of the *FLIP* experiment was to obtain coordinated measurements of acoustic surface scattering, the subsurface bubble field, and sea state. The measurements will be used to (1) understand more fully the conditions imposed by the near-surface environment that affect the performance of sonar signal processing algorithms, and (2) improve high-frequency acoustic models used in sonar system modeling and analysis.

Besides the scattering loss measurements, the experiment also included measurements of the strength and coherence of monostatic backscatter and bistatic forward scatter, which will be discussed in separate reports. Some of the data have been transferred to the Applied Research Laboratory at Pennsylvania State University (ARL/PSU) for processing into estimates of channel scattering function [1] and bistatic forward scatter [2].

The surface forward scattering loss measurements were analyzed for residual loss (defined as loss in excess of spreading and chemical absorption) attributed to resonant extinction from near surface bubbles. This will be referred to as surface bubble loss (SBL). The SBL estimates from the *FLIP* experiment were used to develop a semiempirical predictive model for SBL, which predicts mean energy loss in surface bounce paths due to extinction from near-surface bubbles. We recommend that this new model replace the SBL model currently used. SBL is a key input parameter for predicting bubble attenuation in simulations of weapon systems in near-surface environments.

This work is part of the Office of Naval Technology's Exploratory Development Program with technical management by ARL/PSU. The ONT (now ONR-T) program is primarily concerned with exploratory development within the frequency range of 10 to 500 kHz, with applications directed toward sonar signal processor and performance analysis technologies. A component of the *FLIP* experiment was also carried out as

part of The Technical Cooperation Program (TTCP). Comparative measurements of the ocean bubble layer were made by APL-UW, representing the U.S., and the Institute of Ocean Sciences (IOS), representing Canada. IOS measured the bubble field using its SEASAT instrument package deployed from USNS *De Steiguer* (T-AGOR-12) which kept station nearby during 9 days of the 18-day experiment. Joint analysis of the APL and IOS measurements is continuing; preliminary results of this work were presented last fall [3].

Section 2 describes the *FLIP* experimental measurements. Section 3 reviews the method used for estimating surface bubble loss, and Section 4 summarizes the modeling methods. A discussion and summary are presented in Section 5. Measurement errors are summarized in Appendix A. Additional model/data comparisons are contained in Appendix B.

2. EXPERIMENTAL DESCRIPTION

Figure 1 shows the track of *FLIP* during the experiment. The measurements discussed in this report were made between 18 and 24 January. During this period, wind speeds ranged from approximately 1 to 9 m/s, and the sea often had a large swell component with a period of ~ 11 s and significant wave height ($H_{1/3}$) between 1 and 2 m.

The geometry used for the surface forward scattering measurements is shown in Fig. 2. Signals were transmitted from one of three ITC-1032 transducers suspended from the spar buoy at depths of 27, 57, and 147 m.¹ The spar buoy was tethered to *FLIP* by a 1000-m cable and ranged from 500 to 1000 m from the vessel.

CW pulses (1, 4, or 8 ms) were transmitted at 1-s intervals in a four-pulse sequence, during which the frequency changed from 20 to 50 kHz in 10-kHz steps. A typical run consisted of 200 pings, equivalent to 50 pings of a single frequency transmitted at 4-s intervals.

The signals were received at *FLIP* using a second ITC-1032 transducer located on the tip of the 13-m subsurface boom attached to *FLIP*'s hull at a depth of 28.5 m. The boom was designed for vertical-incidence measurements of the bubble layer but also made an excellent receiver location, since surface scatter could be distinguished from rescatter from the *FLIP*'s hull, which arrived approximately 17 ms after the direct arrival.

Environmental measurements consisted of mean wind speed and direction (10-min averages) taken 10 and 25 m above the sea surface, surface wave-height spectra, air and sea temperature, and conductivity-temperature-depth (CTD) casts (twice daily, typically at 0800 and 2000). Additional details on the environmental measurements are available in Ref. 4.

¹These depths varied ± 0.5 m owing to heave motion of the buoy.

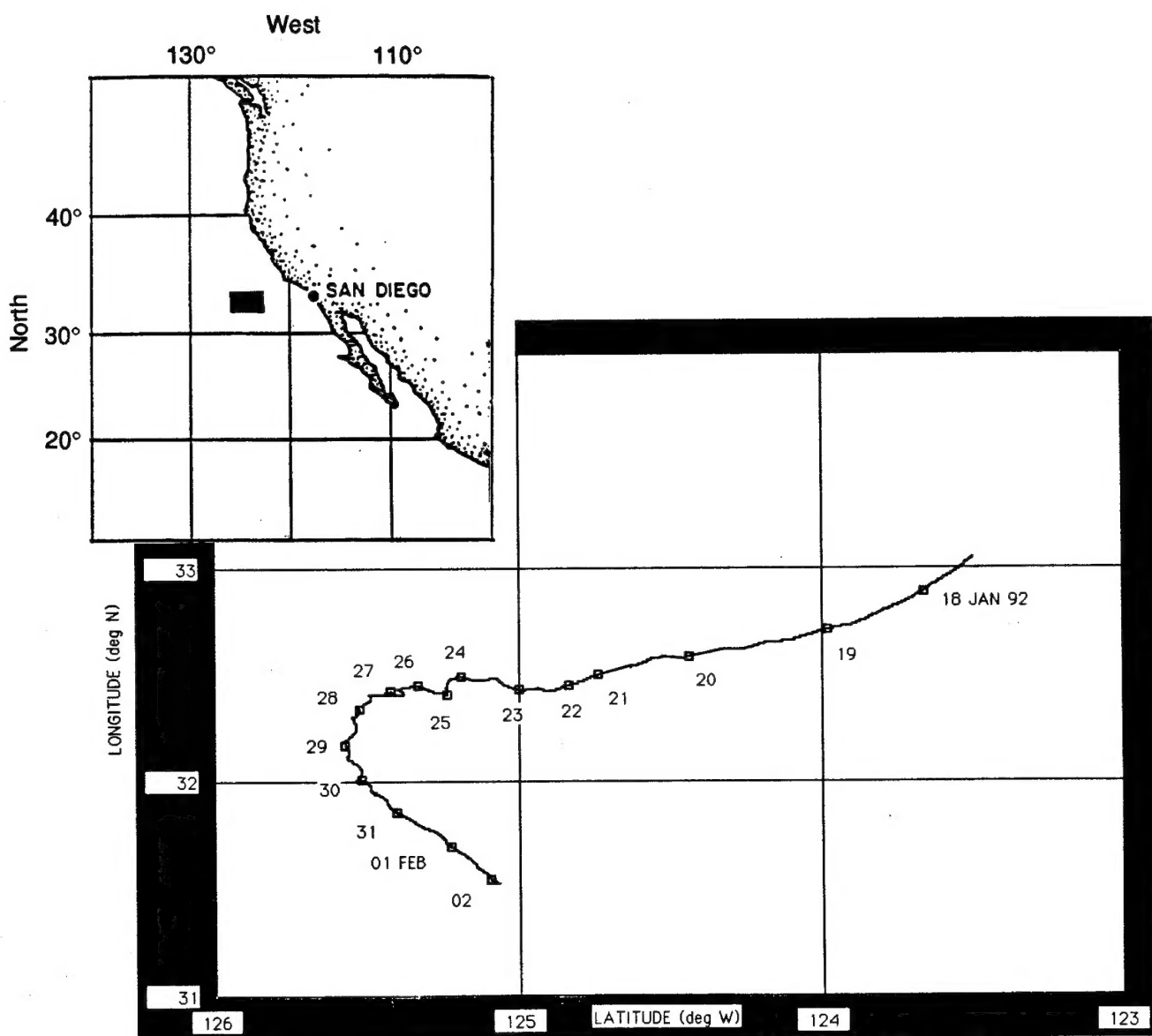


Figure 1. *FLIP* drift track as determined from the GPS navigation system. Locations at 0000 hours local time are indicated along the track.

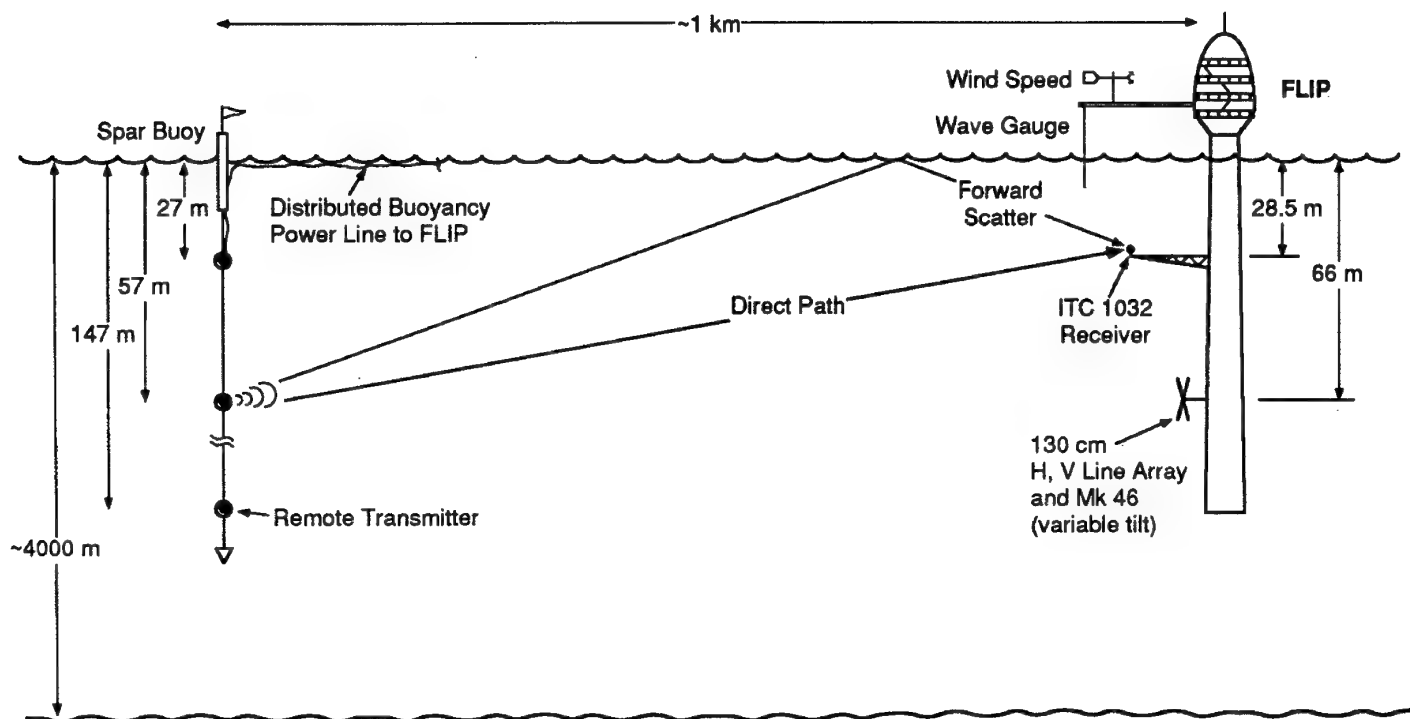


Figure 2. Experimental geometry for surface forward scattering loss measurements. The spar buoy range varied between 500 and 1000 m.

3. DATA ANALYSIS METHODS

3.1 Preliminary Discussion

In general a signal forward scattered from the sea surface experiences both time spreading (pulse elongation) and energy loss. The latter is attributed to the extinguishing effects of the near-surface bubble field, through which surface bounce paths must traverse. This effect is known as surface bubble loss (SBL). Reference 5 gives a model for the time dependence of forward-scattered intensity. This model predicts the build-up and decay of mean intensity as a function of geometry and surface roughness (assuming high frequency limit, Gaussian surface statistics). The model matches closely the ensemble average of simulated forward-scattered pulses using specular point theory [6] as well as data from *FLIP*.

In the absence of attenuation from near-surface bubbles, the time integrated intensity can be modeled with a 0 dB loss, this result having been explicitly proven using the Kirchhoff approximation and confirmed with experimental data [3,7]. We thus estimate SBL by estimating the residual loss (in decibels) in total energy, after accounting for spreading loss and chemical absorption, the latter being temperature and salinity dependent. The SBL estimate is equivalent to the residual loss estimate.

A necessary condition for the 0 dB loss is that the transmit and receive beamwidths be greater than the angular width of the surface-scattered intensity. In practice, this criterion is met with vertical beamwidths of 20–25° and horizontal beam widths of 5–10° [5]. For the *FLIP* experiment, the transmit and receive beams were omnidirectional to avoid any effects caused by narrow beams.

3.2 SBL Estimation Procedure

As noted above, pulse energy is generally spread in time. In the absence of a bubble layer, however, the total energy level scattered from the surface, E_0 , can be computed by

$$E_0 \text{ (dB)} = SL - TL + 10 \log \tau, \quad (1)$$

where TL is transmission loss, which includes geometric spreading and chemical absorption, SL is peak source level, and τ is the pulse length.

For each run, a ray analysis is performed using the nearest-time CTD cast for the sound speed profile. From the ray analysis, we get direct and surface-path eigenrays that match the measured travel times, surface path-spreading loss (typically $20 \log$ of the range), and nominal surface grazing angle (θ). Chemical absorption losses are estimated from [8], based on the temperature and salinity at 30 m.

The output of our acoustic receiving system is a signal mixed down to 5 kHz, with a nominal bandwidth of 10 kHz. The 5-kHz signal is digitized at a 20-kHz rate, and later digitally bandpass filtered between 4 and 6 kHz to remove distortions and noise that may have been introduced during the conditioning phase. Echo envelopes are computed from the Hilbert transform of each ping. We form an equivalent estimate of energy from the data, E_1 , by integrating the intensity over the time span of each surface arrival (see Figs. 3 and 4). Note that the leading edges of the direct path are first aligned to remove effects due to source and receiver motion. The integration is truncated approximately 17 ms after the start of direct arrival to avoid integrating rescatter from *FLIP*'s hull.² For each ping an estimate of the residual loss is computed which is equal to $E_0 - E_1$. The residual loss is our estimate of the surface bubble loss. The mean loss $\langle \text{SBL} \rangle$ is computed from the energy ensemble average for each run; i.e., $\langle \text{SBL} \rangle = E_0 - \langle E_1 \rangle$, where $\langle E_1 \rangle$ represents time integration of the ensemble average.

In runs for which the direct and surface paths overlap, it is not possible to integrate the surface path separately. Here, we use an alternate method [9] for estimating the surface bubble loss based on fitting the ensemble mean of surface-scattered intensity using the pulse elongation model in [5]. The pulse elongation model requires an estimate of rms slope, and the surface loss is then adjusted to fit the data.

The two SBL estimation procedures are illustrated in Figs. 3 and 4 using data from run 114 made during conditions characterized by fairly frequent white capping (Beaufort Wind Scale 4–5) with $U = 7$ m/s. To fit the data ensemble mean with the pulse elongation model, the 30-kHz data (Fig. 3) requires 3 dB of SBL, while

²Typically less than 1% of the energy arrives after this point, amounting to negligible error.

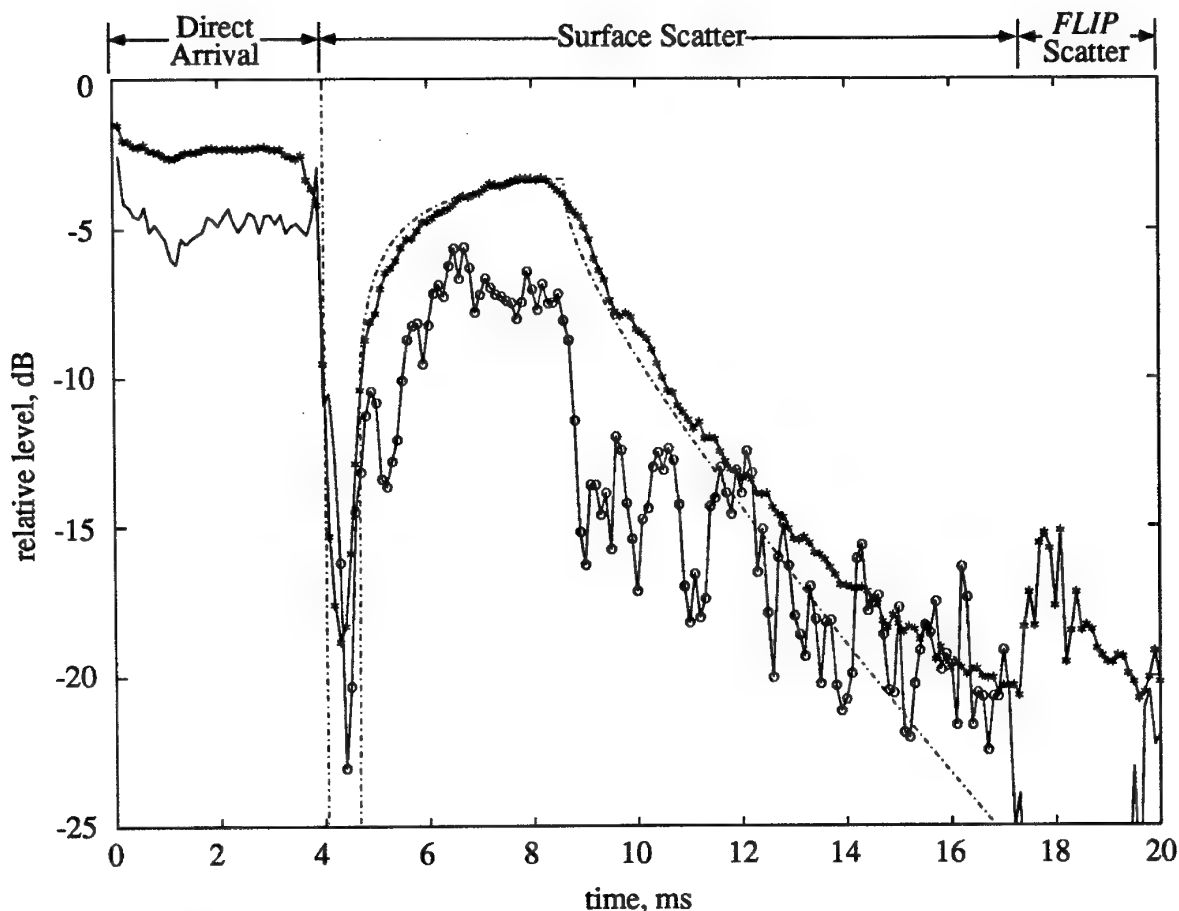


Figure 3. Surface forward-scattered intensity vs time for 30-kHz run 114, showing ensemble mean (*) and ping number 10 (o). The dashed line represents the time spread model in Ref. 5 fitted to the ensemble data; in this case, the model is given an SBL input of 3 dB in order to fit the data.

the 40-kHz data (Fig. 4) requires 4.5 dB of SBL. These estimates match closely those derived by direct integration (3.0 and 4.6 dB). In each figure, ping number 10 for each frequency³ is shown including the region of integration for computing E_1 , starting at the beginning of the surface arrival and ending just before rescatter from *FLIP*'s hull commences (~17 ms).

³Each 30 kHz ping is transmitted 1 s before each 40 kHz ping.

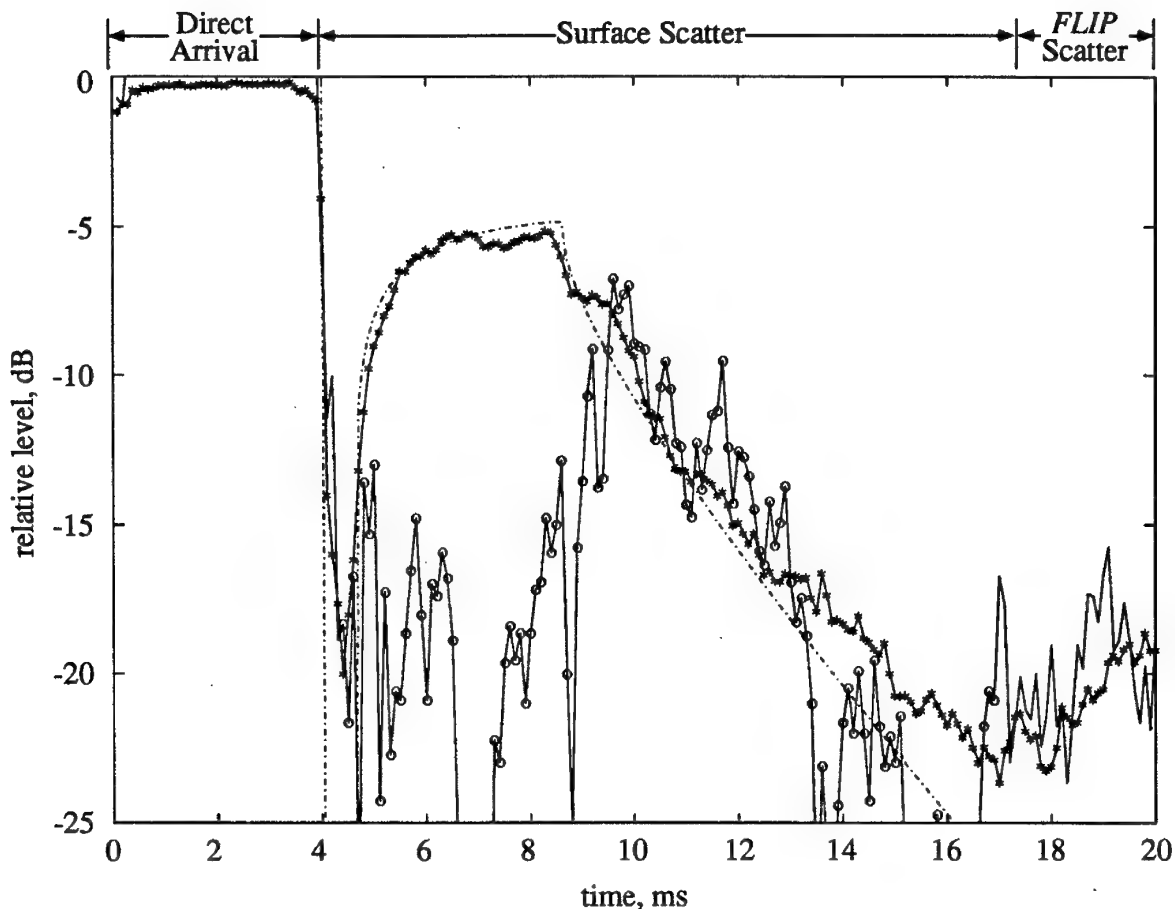


Figure 4. Surface forward scattered intensity vs time for 40-kHz run 114 showing ensemble mean (*) and ping number 10 (o). The dashed line represents the time spread model in Ref. 5 fitted to the ensemble data; in this case, the model is given an SBL input of 4.5 dB in order to fit the data.

3.3 Results

Table I summarizes the SBL database derived from the *FLIP* experiment. When possible, the direct integration method has been used to estimate SBL since with this method we can also estimate ping-to-ping fluctuations in SBL. For example, the 30-kHz ping number 10 experienced a 6.5 dB SBL compared with an ensemble mean loss of 3 dB, and the 40-kHz ping number 10 experienced a 10 dB loss compared with an ensemble mean loss of 4.5 dB. Clearly, fluctuations in SBL can be large. For a

Table I. Summary of SBL database derived from FLIP experiment.

	EXP. RUN	RANGE (m)	FREQ. (kHz)	θ (deg)	WIND ^a (m/s)	(SBL) (dB)
1	109	874	20	10.9	8.0	1.2
2	109	874	30	10.9	8.0	3.7
3	110	877	20	10.9	7.8	1.0
4	110	874	30	10.9	7.8	3.8
5	110	874	40	10.9	7.8	5.2
6	110	874	50	10.9	7.8	3.5
7	111	855	20	4.5	7.8	2.7
8	111	855	30	4.5	7.8	6.3
9	111	855	40	4.5	7.8	9.6
10	111	855	50	4.5	7.8	9.0
11	114	995	20	11.1	7.0	1.2
12	114	995	30	11.1	7.0	3.0
13	114	995	40	11.1	7.0	4.6
14	114	995	50	11.1	7.0	4.0
15	115	995	20	11.1	5.3	1.2
16	115	995	30	11.1	5.3	2.4
17	115	995	40	11.1	5.3	2.6
18	115	995	50	11.1	5.3	1.6
19	116	540	20	17.6	4.1	1.7
20	116	540	30	17.6	4.1	0.2
21	116	540	40	17.6	4.1	0.1
22	116	540	50	17.6	4.1	0.2
23	117	540	20	17.6	4.1	1.7
24	117	540	30	17.6	4.1	0.8
25	117	540	40	17.6	4.1	0.4
26	117	540	50	17.6	4.1	0.5
27	118	532	20	9.1	4.1	0.5
28	118	532	30	9.1	4.1	0.5
29	118	532	40	9.1	4.1	2.6
30	118	532	50	9.1	4.1	3.0
31	132	1000	20	9.3	6.2	-0.8
32	132	1000	30	9.3	6.2	1.7
33	132	1000	40	9.3	6.2	1.5
34	132	1000	50	9.3	6.2	2.5
35	133	668	20	14.3	4.3	-0.1
36	133	668	30	14.3	4.3	0.2
37	133	668	40	14.3	4.3	-0.2
38	133	668	50	14.3	4.3	0.2
39	138	666	20	14.5	4.4	0.7
40	138	666	30	14.5	4.4	1.3
41	138	666	40	14.5	4.4	2.5
42	138	666	50	14.5	4.4	0.2
43	139	666	20	14.5	4.8	0.7
44	139	666	30	14.5	4.8	1.3
45	139	666	40	14.5	4.8	1.5
46	139	666	50	14.5	4.8	0.2

^aMeasured 10 m above sea surface.

useful measure of the size of these fluctuations we adapt an expression for transmission loss studies [10] to our estimates of surface loss due to bubbles (SBL) and define

$$\text{SBL}_+ = 10 \log[E_0/(\langle E_1 \rangle - \sigma)]$$

and

$$\text{SBL}_- = 10 \log[E_0/(\langle E_1 \rangle + \sigma)] ,$$

where σ is the standard deviation of the time-integrated intensity; SBL_+ represents a typical high loss value, and SBL_- represents a low loss value. We expect the majority of ping-to-ping fluctuations in surface loss to lie between these bounds. From the *FLIP* data, the low and high loss bounds are such that $\text{SBL}_- \approx \langle \text{SBL} \rangle - 3$ dB and $\text{SBL}_+ \approx \langle \text{SBL} \rangle + 5$ dB. The data suggest that fluctuations in loss estimates tend to be dominated by fluctuations associated with incoherent scattering from a random surface [11]. Under these conditions, it is very difficult to resolve the component of variation due solely to the bubble field.

4. MODEL FOR SURFACE BUBBLE LOSS

4.1 Preliminary Discussion

The two-way transmission loss attributable to bubbles [12] can be generalized to an arbitrary grazing angle, giving the following expression for SBL [5].

$$\text{SBL (dB)} = \frac{8.686}{\sin \theta} \int_D s_e(z) dz , \quad (2)$$

where θ is the nominal grazing angle for surface arrivals; $s_e(z)$ is the total extinction cross section per unit volume, which is integrated over the bubble layer thickness D . The bubble layer thickness in this case corresponds to the average entrainment depth of resonant bubbles.

We use Eq. (2) as a guide for developing a predictive model for SBL as a function of grazing angle θ and frequency, with wind speed as an environmental predictor of both bubble concentration and entrainment depth. The $1/\sin \theta$ dependence is well supported by the *FLIP* database and other measurements [13], but modeling the depth-integrated $s_e(z)$ is more difficult. In principle, one can infer the necessary depth-integrated properties of $s_e(z)$ from vertical-incidence sonar measurements. But predicting bubble attenuation effects from bubble scattering data have, to date, given inconsistent results [13,14]. The source of error may be in the bubble damping constant, or perhaps in assumptions regarding the horizontal and vertical variations in bubble density.

4.2 Modeling Surface Bubble Loss

The approach we take is to use the actual surface loss data to estimate parameters in a semiempirical model of the form

$$\begin{aligned} \text{SBL (dB)} &= \frac{p_1}{\sin \theta} U^{p_2} F^{p_3} , & U \geq 4 \text{ m/s} \\ \text{SBL (dB)} &= \text{SBL}|_{U=4} e^{10(U-4)} , & U < 4 \text{ m/s} , \end{aligned} \quad (3)$$

where U is wind speed measured 10 m above the sea surface, F is acoustic frequency in kilohertz, and parameters p_1 to p_3 are derived from the data. We assume bubble production and entrainment follows a wind speed power law, consistent with well

established power law forms for whitecap coverage [15]; from typical bubble size spectra [16], we would also expect the frequency dependence to be a power law. We retain the $1/\sin \theta$ dependence to be consistent with Eq. (2), and include a wind speed threshold of 4 m/s to account for the breaking wave threshold, or Beaufort velocity, often reported to be between 2 and 5 m/s. For the *FLIP* measurements, we observed essentially no surface loss for wind speeds less than 4 m/s. The transition to 0 dB loss is approximated, primarily for continuity in simulations, by a steep exponential decay such that the loss at 3.5 m/s is about 1% of the loss at 4 m/s (i.e., $\text{SBL}|_{U=4}$).

The three parameters are estimated by fitting a nonlinear curve to Eq. (3), using the *FLIP* data in Table I (freq, U , θ , and $\langle \text{SBL} \rangle$). The Nelder-Meade algorithm⁴ is used to minimize the total absolute value error between model and data vectors. The fitted model parameters are

$$\begin{aligned} p_1 &= 1.26 \pm 0.48 \times 10^{-3} \\ p_2 &= 1.57 \pm 0.23 \\ p_3 &= 0.85 \pm 0.22 , \end{aligned}$$

where the \pm values represent the 95% confidence interval for the parameter estimates, as generated by the bootstrap algorithm [17].

⁴See MATLAB User's Guide.

5. DISCUSSION AND SUMMARY

Figures 5–8 show representative model/data comparisons between 20 and 50 kHz. To show data collected at different grazing angles, all data have been normalized to a 10° grazing angle for this comparison, using the formula

$$\text{SBL}(10^\circ) = \frac{\sin \theta}{\sin 10^\circ} \text{SBL}(\theta), \quad (4)$$

where $\text{SBL}(\theta)$ is the actual measured loss⁵ at grazing angle θ .

The scatter in the data generally increases for smaller wind speeds, owing in part to measurement uncertainties (approximately ± 2.5 dB; see Appendix A). Nevertheless, the model provides a reasonable representation of the data, with nearly all data points falling within ± 2 dB of the predicted curve. The sharp drop in each predicted curve at a wind speed equal to 4 m/s represents the wind speed threshold for the onset of breaking waves and subsequent production of bubbles. The entire model is now summarized with parameters

$$\begin{aligned} \text{SBL} &= \frac{1.26 \times 10^{-3}}{\sin \theta} U^{1.57} F^{0.85}, \quad U \geq 4 \text{ m/s} \\ \text{SBL} &= \text{SBL}|_{U=4} e^{10(U-4)}, \quad U < 4 \text{ m/s}, \end{aligned} \quad (5)$$

where SBL is in decibels. Note that grazing angle θ must be restricted to $\theta > 0^\circ$.

Using the known environmental conditions and fixed experimental geometries from these two experiments, the model describes the *FLIP* measurements to within ± 2 dB, with a total rms error of approximately 1 dB. Fluctuations in model estimates using the bootstrap algorithm gave similar values. In general, however, uncertainties in environmental conditions and run geometry, e.g., the grazing angle of the surface bounce path, will tend to magnify errors in model prediction, and we set a more realistic bound for model uncertainty to ± 3 dB. Additional model/data comparisons using SBL measurements from two other experiments are shown in Appendix B.

The SBL model predicts the mean energy loss in surface bounce paths due to extinction from near-surface bubbles, where the energy, or time-integrated intensity,

⁵The three negative values in Table I have been set to zero for this comparison.

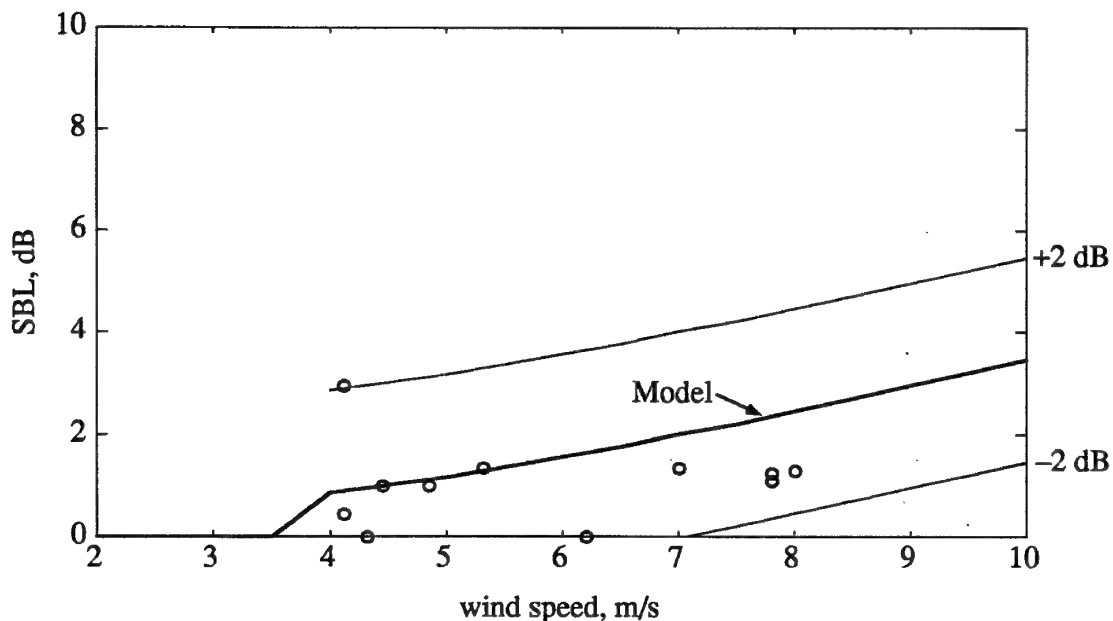


Figure 5. Comparison of SBL model with measured 20-kHz data from FLIP. Data from various grazing angles have been normalized to 10° grazing angle according to Eq. (5). Upper and lower lines represent ± 2 dB interval about the predicted curve.

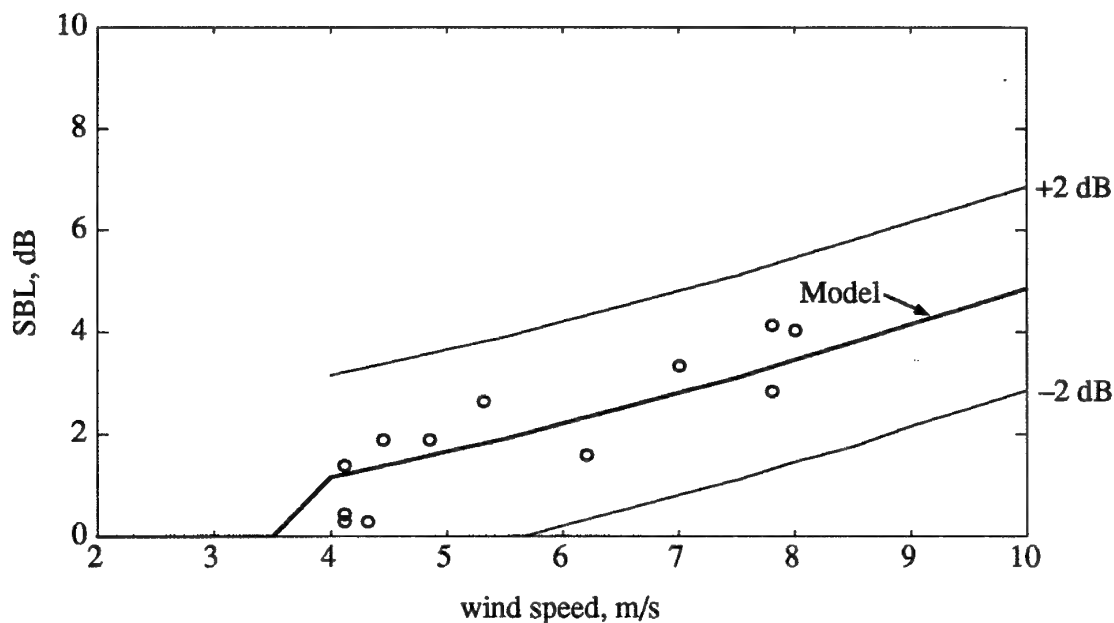


Figure 6. Comparison of SBL model with measured 30-kHz data from FLIP. Data from various grazing angles have been normalized to 10° grazing angle according to Eq. (5). Upper and lower lines represent ± 2 dB interval about the predicted curve.

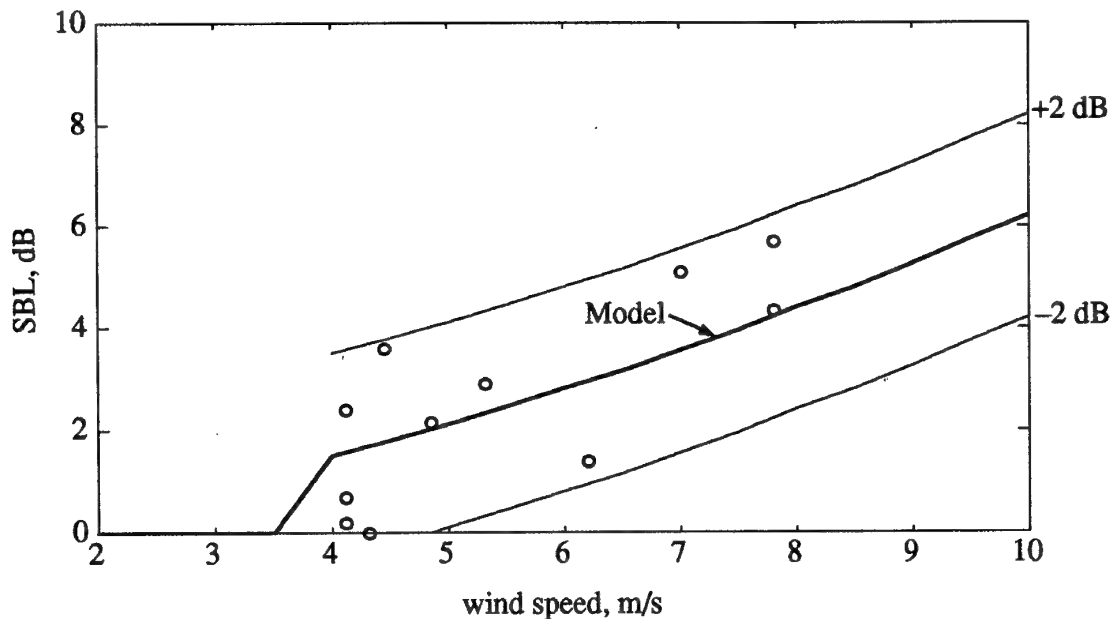


Figure 7. Comparison of SBL model with measured 40-kHz data from FLIP. Data from various grazing angles have been normalized to 10° grazing angle according to Eq. (5). Upper and lower lines represent ± 2 dB interval about the predicted curve.

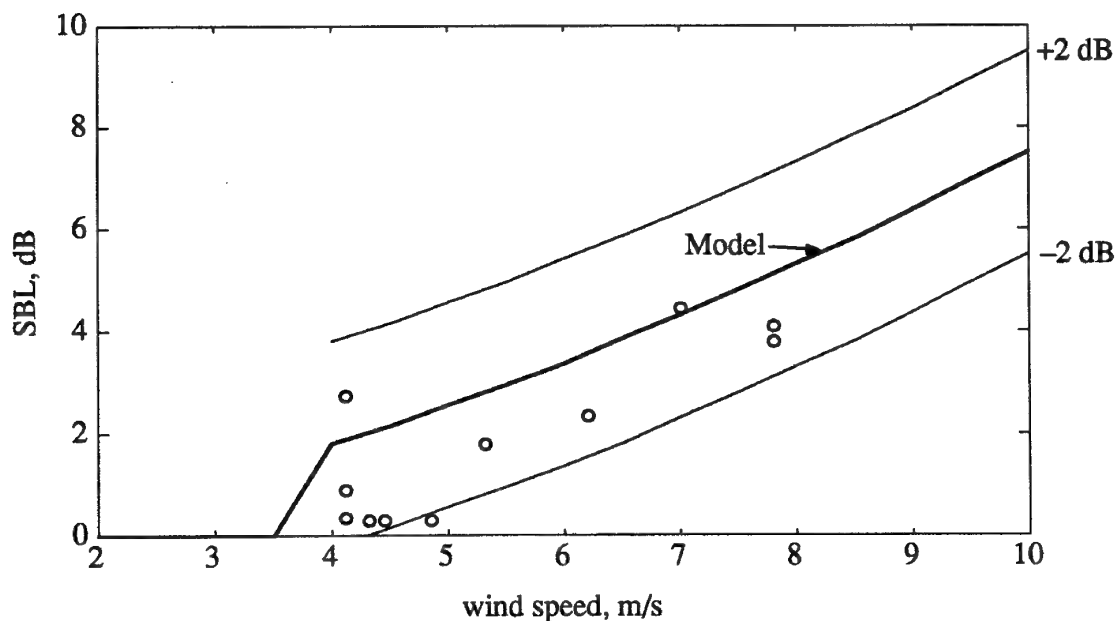


Figure 8. Comparison of SBL model with measured 50-kHz data from FLIP. Data from various grazing angles have been normalized to 10° grazing angle according to Eq. (5). Upper and lower lines represent ± 2 dB interval about the predicted curve.

can be modeled with a 0 dB loss in the absence of bubbles. Model performance will be degraded in conditions under which the 0 dB loss case cannot be assumed. Some examples where this could occur are as follows:

- Model used to simulate data gathered with narrow transmit and receive beam patterns (see Section 3.1).

Data losses will be greater than simulated SBL because of an undersampling of the angular distribution of scattered intensity in the data.

- SBL model used to simulate loss in the peak value of short-pulse data.

A short pulse is defined as one with pulse duration τ much less than the characteristic pulse elongation time T for surface-scattered arrivals. In such cases, the intensity will not have reached steady state, and the total energy will be underestimated when based on estimates of peak intensity, resulting in data losses greater than the simulated losses. Note that ideally the time interval of intensity integration should be 2–3 times the characteristic pulse elongation time T [5]. A rough guide is $T = 4.6R$, where T is in milliseconds and range R is in kilometers.

- SBL model used to simulate conditions characterized by a highly directional surface wave spectrum. In this case, the distribution of surface slopes can no longer be considered isotropic, and the model error will depend on the exact orientation of the surface bounce paths with respect to the surface waves.

Expected uncertainties in the new SBL model are summarized as follows:

- The uncertainty in predicted mean SBL is ± 3 dB.
- The ping-to-ping fluctuations in SBL will be approximately bounded by -3 and $+5$ dB about the predicted mean SBL value, based on the SBL_+ and SBL_- estimates discussed in Section 3.3.

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APPENDIX A

Calibration and Measurement Errors

The transmitting system (three ITC projectors and 1000 m of EM cable) and receiving systems were calibrated at the APL-UW calibration facility during the month before the experiment; overall accuracy of the calibration system is ± 1.5 dB.

In the course of analyzing the data, however, we observed a systematic bias, particularly for runs made at 50 kHz. For example, measurements gathered under conditions characterized by wind speeds $\lesssim 4$ m/s and the absence of wavebreaking activity for several hours are expected to show a 0 dB loss. This was the case for the 30-kHz runs (within ± 2 dB), but the 50-kHz runs showed a systematic average *negative* loss of -4 dB, while the 20-kHz runs showed a small average positive loss of 1.2 dB. We attribute this result to differences in cable loading during the calibration (cable spooled) and during the *in situ* measurements (cable laid out in seawater). It is not possible to reconstruct the exact *in situ* complex impedance of the cable. But simple modeling of the cable/transducer system using a range of possible lumped circuit parameters reproduced a similar trend for the frequencies farthest from the transducer resonance (20 and 50 kHz). Thus, based on five *in situ*, bubble-free measurements of surface loss, we have adjusted the source level from what our calibrations would normally give in the following way: 20 kHz (down by 1.2 dB), 30 kHz (no change), 40 kHz (no change), 50 kHz (up by 4.0 dB). Similar estimates of the source level bias were made using one run with an extremely stable direct path.

Another source of error is the *TL* estimate in Eq. (1), which is divided into (1) chemical absorption error (± 1.5 dB) and (2) spreading loss error (± 1 dB). The error component due to absorption is based on the expected variation ($\pm 10\%$) for the temperature- and salinity-dependent absorption coefficient, evaluated at 50 kHz and using the maximum range of our measurements (1000 m). The error component due

to spreading is caused by differences in sound speed conditions between the actual experimental run and what was measured during the CTD cast. As a guide, we use the average difference between expected spreading loss for isovelocity conditions (approximately $20 \log$ of the range) and the ray trace estimate, setting this error to ± 1 dB.

The calibration errors, errors in the TL estimate, and errors due to sample size (less than 1 dB in our data) sum independently, giving approximately ± 2.5 dB for an estimate of the total error that applies independently to each experimental run.

APPENDIX B

Additional Model/Data Comparisons

The SBL measurements from the *FLIP* experiment were made under open ocean, unlimited fetch conditions, with the received signal consisting entirely of direct and surface bounce paths. They represent the largest set of combined acoustic and sea state measurements from which to generate a semiempirical model for SBL. A smaller set of SBL measurements, taken in shallow water conditions, was obtained in the Quinault [9] and Whidbey Island [13,18] experiments. Model comparisons using these data in addition to the *FLIP* data are shown in Figs. B1–B3. Note that as in Figs. 5–8 data have been normalized to 10° grazing to facilitate comparison.

In the Quinault experiment, SBL was measured in continental shelf waters (depth 50 m) approximately 17 km off the Washington coast. In terms of sea surface properties, this site can be considered open ocean. In the Whidbey Island experiment, SBL was measured in inland waters (depth 30 m) near the junction of the Strait of Juan de Fuca and Puget Sound. Sea surface properties at this site are strongly dependent upon wind direction. In both these experiments the received signal consisted of a mixture of surface and bottom paths. The Quinault measurements showed evidence of very high losses that in some cases did not correspond with wind speed. For the Whidbey Island data the severe fetch limitation may be a factor in determining bubble dispersion and SBL, and uncertainties in wind speed measurements may be a source of error.

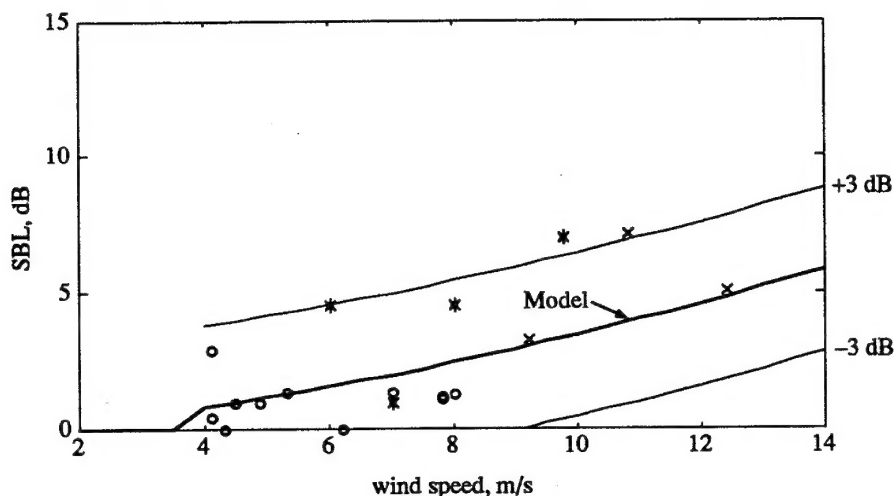


Figure B1. Comparison of SBL with measured 20-kHz data from FLIP (open circles), Quinault (stars), and Whidbey Island (crosses). Data from various grazing angles have been normalized to 10° grazing angle according to Eq. (5). Upper and lower lines represent ± 3 dB interval about the predicted curve.

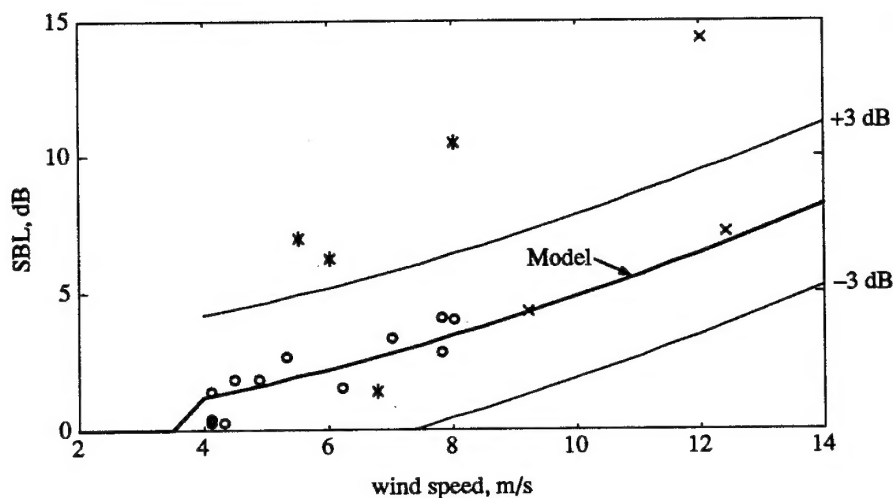


Figure B2. Comparison of SBL with measured 30-kHz data from FLIP (open circles), Quinault (stars), and Whidbey Island (crosses). Data from various grazing angles have been normalized to 10° grazing angle according to Eq. (5). Upper and lower lines represent ± 3 dB interval about the predicted curve.

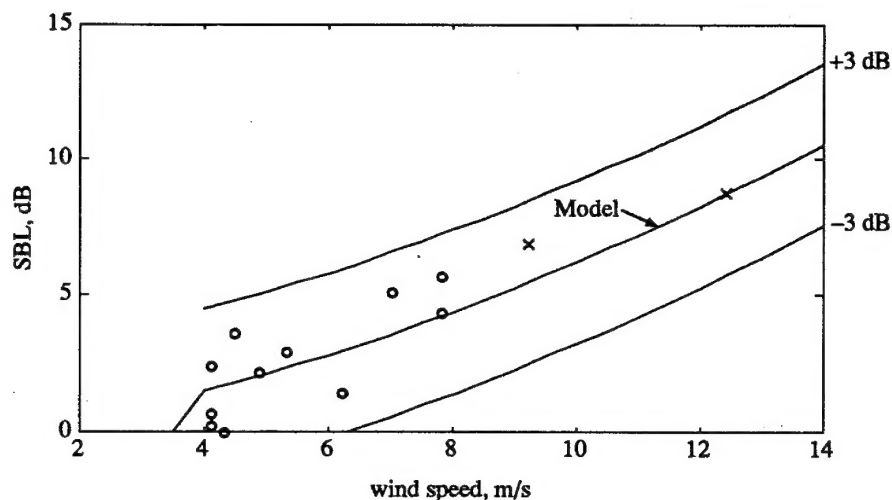


Figure B3. Comparison of SBL with measured 40-kHz data from FLIP (open circles), and Whidbey Island (crosses). Data from various grazing angles have been normalized to 10° grazing angle according to Eq. (5). Upper and lower lines represent ± 3 dB interval about the predicted curve.

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